RESULTS FROM TESTS OF THE FAST ALTERNATIVE CRYOGENIC EXPERIMENT TESTBED (FACET)

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Abstract

To address the gap in manifest opportunities for low temperature microgravity payloads that has accompanied the start of the build era for the International Space Station (ISS), development of a new facility compatible with one or more carriers in the baseline shuttle manifest has been undertaken. This new facility is called the Fast Alternative Cryogenic Experiment Testbed (FACET). During the past year, a ground prototype was designed, built and tested to prove the feasibility of a flight facility for conducting low temperature microgravity fundamental physics investigations within the constraints of the Space Shuttle Hitchhiker Siderail carrier.

To accomplish this, significant reductions in cryostat mass and volume, while maintaining cryogen lifetime performance, were necessary. Measurements of ground performance agree well with theoretical modeling and indicate that a flight system would be capable of cooling an instrument for nearly the full duration of even the longest shuttle missions (16 days). In addition, a new modular electronics architecture has been demonstrated, which will provide added flexibility for reflights of the facility with different investigations. This project serves as a pathfinder for the Low Temperature Microgravity Physics Facility (LTMPF).

Background

The Fast Alternative Cryogenic Experiment Testbed (FACET) project was a one year proof of concept study to demonstrate, through the design, construction, and test of subsystem prototypes, the feasibility of flying cryogenic payloads aboard the Space Transportation System (STS) (a.k.a. the space shuttle) during the International Space Station (ISS) build era. This paper summarizes the development of the key payload prototype subsystems built and tested. A more detailed description of the cryostat and its development is given elsewhere[1].

The start of the build era for the International Space Station (ISS) has resulted in the end of regularly scheduled microgravity science opportunities such as the United States Microgravity Payload (USMP) missions on which the Lambda Point Experiment (LPE) and Confined Helium Experiment (CHeX) flew. In addition, the ISS is not scheduled to be completed enough for the planned Low Temperature Microgravity Physics Facility (LTMPF) to conduct experiments until 2003 at the earliest. This situation not only increases the backlog of existing low temperature microgravity science experiments, but it also compromises the ability to conduct any incremental tests of scientific or technological concepts in microgravity until after the start of the Space Station era.

To address this gap in flight opportunities, several approaches were investigated. An earlier flight of the planned LTMPF is dependent not only on timely completion of the ISS, but also relies on an accelerated funding schedule to develop the LTMPF itself. The size and weight of the existing Low Temperature Platform (LTP) cryostat[2] used for LPE and CHeX requires a cross-bay carrier mount which is not in the baseline space shuttle manifest. Furthermore, in the case of an ISS schedule slip, the carriers most likely to be manifested are pressurized modules, such as SPACELAB, which are not compatible with crossbay carriers.

The other option investigated was the possibility of a new facility compatible with one or more carriers in the baseline shuttle manifest. This new facility is called the Fast

Alternative Cryogenic Experiment Testbed (FACET).

Payloads are accommodated in the space shuttle by way of carriers. Each of these carriers brings with it a fixed set of capabilities (mass, volume, telemetry, etc.) which in turn affects their manifesting opportunities. A carrier trade study was conducted for the FACET concept, and it was determined that the carrier whose capabilities most closely matched the capabilities of the current Low Temperature Platform, with the highest probability of manifesting opportunities, with the lowest demand on resources, was the Hitchhiker siderail (HH-S) carrier.

Many aspects of the HH-S carrier increase the probability for manifesting opportunities. Hitchhiker has historically been manifested 4 times a year, and has flown along with a wide range of payload masses. Hitchhiker payloads have flown during: a (5,586 lb.) TDRSS satellite deployment mission, MIR servicing missions, SPACELAB pressurized module missions, as well as the United States Microgravity Payload (USMP) series on which LPE and CHeX flew. The hitchhiker office has an agreement to fly on a "mass available" basis during the station build era. In fact, Hitchhiker Siderail payloads have flown during the mission which deployed the first US module of the ISS, the Unity module, and the first servicing mission. The roughly order of magnitude smaller mass of the hitchhiker when compared to other carriers promises more manifest opportunities.

The Hitchhiker project was established by the NASA Headquarters Office of Space Flight (OSF) to develop and operate carrier systems for low-cost and quick-reaction accommodation of secondary payloads on the Space Shuttle. The FACET payload has been designed as a "rapid response" payload, only requiring 9 months from approval to launch.

The FACET project objectives were derived from the ultimate goal of producing a simple, low cost, facility providing frequent flight opportunities before the availability of the Low Temperature Microgravity Physics Facility (LTMPF) for existing flight definition Principal Investigators. The prototype was to demonstrate, within tight schedule and cost constraints, the feasibility of a flight system by the test of ground hardware of which the technical approach could be used to develop low cost flight hardware. It was desired that the flight system should be compatible with multiple reflights, each capable of supporting a different investigation.

In this development, cost and schedule were the driving constraints, with technical scope and performance secondary.

The science objectives to be accomplished within the FACET facility are related to the manipulation and measurement of the thermodynamic variables associated with processes that occur at liquid helium temperatures in a microgravity environment.

The performance requirements were derived from minimum mission requirements negotiated with the backlogged investigators or their representatives.

Payload Concept

A block diagram of the FACET payload is shown in Figure 1. The prototype subsystems that have been developed are labeled in bold type. Items labeled in plain type were simulated using ground support equipment. Items labeled with italicized text were not part of this prototype effort.

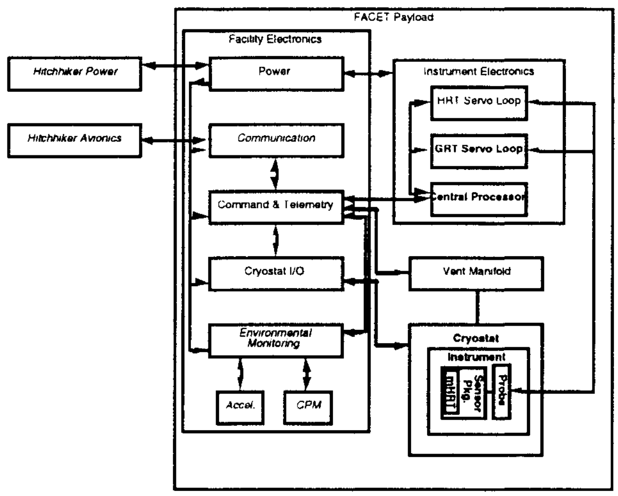

Figure 1 FACET Payload Block Diagram.

The functional breakdown of the FACET payload is nearly identical to the Low Temperature Platform (LTP) used for the Lambda Point Experiment (LPE) and the Confined Helium Experiment (CHeX).[3]

The components can be organized into four major subsystems: cryostat assembly, instrument, facility electronics, and instrument electronics.

The cryostat assembly includes the dewar itself, as well as the vent plumbing manifold necessary to alter the vent rates while on orbit. Unlike the LTP, however, the FACET payload does not have a vacuum pump. This is due to mass constraints and the fact that the Hitchhiker Siderail (HH-S) carrier does not provide power during the 65 - 161 hour period between last servicing and launch.

The instrument needs to provide a structure for mounting the experiment specific sensor package. This structure needs to be constructed in such a way as to provide several layers of thermal control. The instrument also needs to provide a way to admit and thermally isolate the helium sample under study.

The facility electronics provide five principal functions. Power is filtered, converted, and distributed within the payload. It provides the communications interface with the Hitchhiker avionics. It processes commands and telemetry. It monitors cryostat housekeeping data. It is also designed to monitor the two principal sources of environmental interference for low temperature microgravity fundamental physics instruments. Therefore it includes a Charged Particle Monitor (CPM) and an accelerometer to measure g-jitter.

The exact functions of the instrument electronics will be somewhat experiment specific. However, all of the backlogged low temperature microgravity science experiments require several channels of commandable thermal control, divided between Germanium Resistance Thermometry (GRT) and High Resolution Thermometry (HRT).

Due to tight development constraints, prototypes of only a few subsystems of the payload could be developed. The technology readiness level of all subsystems within the proposed flight payload was assessed, and those subsystems requiring the most development were the ones chosen for prototype development. All subsystems not demonstrated by the development of prototype hardware can inherit design elements from other flight qualified systems. All interfaces are well understood.

Only a few flight elements are missing from the prototype cryostat. Among these are the burst disks required to meet shuttle safety requirements[4] for cryogenic payloads, and motor driven cryovalves. In both cases, locations and envelopes have been specified in the design for known Commercial Off The Shelf (COTS) items to be installed in a flight article. The motor driven cryovalves are necessary to reduce the heat leak to the helium reservoir, the majority of which in the prototype is due to the radiated heat leak around the actuators for the manual cryovalves. In addition, a flight article would require a phase separator of the type developed for SHOOT[5], which would be fed by Liquid Acquisition Devices (LADs)[6], as well as a "standard" sintered stainless steel porous plug.

Due to the development constraints, it was decided not to include a cryo pump of the type required for previous flight experiments[7] in the prototype instrument. However, the location and envelope has been specified in the design for such an item to be installed in a flight article. The development constraints also precluded any design effort to eliminate heating caused by launch vibrations[8] to levels where an exchange gas would not be necessary in the instrument guard vacuum cavity during launch. The pneumatically operated, normally closed cryovalve used in the prototype has not been qualified for flight use, but a valve with identical function and smaller envelope has been[9].

Within the instrument electronics, due to tight development constraints, the readout for Superconducting Quantum Interference Device (SQUID) sensors was not prototyped. Flight qualified systems[10], however, have been developed, the approach of which should be easily adaptable to our architecture.

The facility electronics requirements for FACET are similar to previously flown low temperature microgravity physics experiments[3], and thus were not prototyped. In fact, Ground Support Equipment (GSE) from those previous flight experiments was used to simulate the facility electronics interface to the instrument electronics and cryostat during testing of those prototype subsystems.

Mission Concept

The scenario for system level activities begins with the delivery of the investigator's flight instrument to the Jet Propulsion Laboratory (JPL) and ends after post flight checkout. System integration & test is complete when the experiment specific hardware is installed and working within the flight facility. Environmental test verifies the system's compliance with shuttle requirements associated with the launch and/or space environment. Tests may include; random vibration tests, modal tests, thermal/vacuum tests, and electromagnetic interference (EMI) tests as well as electromagnetic compatibility (EMC) tests. Before the system leaves JPL, all shuttle safety verification requirements (analysis, etc.) must also be completed.

The next level of integration and testing occurs at the Goddard Space Flight Center (GSFC) in Maryland where the flight system is combined with the carrier and tested for EMI/EMC compatibility at the payload level.

The hardware is then shipped to Kennedy Space Center (KSC) in Florida. After a post shipment checkout, the hardware is integrated with the shuttle orbiter in the Orbiter Processing Facility (OPF). From here the orbiter proceeds to the Vehicle Assembly Building (VAB), where among other things, the shuttle is integrated with the Solid Rocket Boosters (SRBs). During this approximately week long period there is no payload access. The shuttle then rolls out from the VAB to the launch pad, where the payload is accessible again. Cryogenic servicing can take place at the pad starting after the arrival of the shuttle at the launch pad (approximately 1 month before launch) and ending 65 hours before nominal liftoff (L-65 hours). Launch windows (depending on mission) can last from less than an hour to no more than 96 hours. Following the LPE/CHeX timeline, within 2 days after launch the system is pumped down & calibrated and ready to begin measurements in microgravity. After the shuttle lands, de-integration of the system from the shuttle and the hitchhiker carrier is followed by any post flight testing and calibration that is required by the individual investigator.

In manner nearly identical to the USMP missions, payload command and telemetry is achieved through Ground Support Equipment (GSE) Workstations at a Payload Operations Control Center (POCC) via the Johnson Space Center (JSC). The Hitchhiker POCC is at GSFC. NASA would provide computer compatible media of the payload data and standard orbit, attitude, and ancillary data for test purposes and for flight acquired data.

Cryostat Results

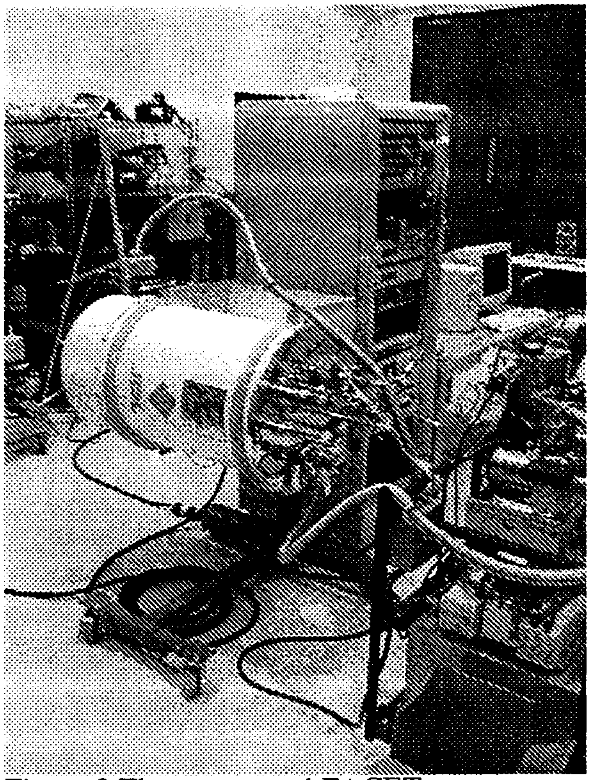

Figure 2 The prototyped FACET cryostat

The cryostat is a hybrid solid neon - liquid helium with "folded tube" G-10 supports. This hybrid approach was taken in part to provide adequate on-orbit lifetime for instruments with high (conducted) heat loads from the instrumentation wiring. There are two vapor cooled shields, in addition to the shield attached to the neon reservoir. The instrument cavity has an interior diameter of 16.51 cm and a depth of 30.48 cm, exceeding the development requirement. The instrument cavity has a vacuum independent of the cryostat vacuum when sealed with the instrument cold flange (and pumped through an instrument provided instrument guard vacuum vent). Heat transfer from the instrument to the helium is accomplished via conduction through the (annular) reservoir's walls. There exist field joints in all vapor cooled shields at the same axial location as the cold flange joint to aid in integration. The shield closure plates and warm flange (collar) interface are modular to accommodate a wide variety of instrument input/output. A photograph of the cryostat is shown in Figure 2.

Measurements of ground performance during simulated on orbit operation agreed well with numerical modeling of the cryostat. The model predicted temperatures and heat flow data inside the prototype cryostat during simulated on orbit operation are shown in Figure 3. The numbers in parentheses are the actual data from simulated operation. Note that the heat flow into the helium tank is dominated by radiation of 36 mW (from leaks around the cold valve actuators).

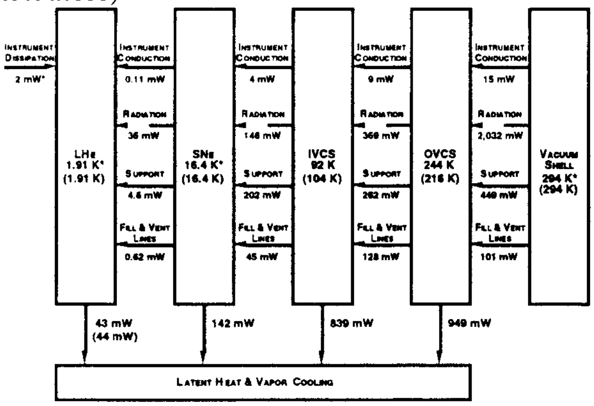

Figure 3 Steady State Model Predictions. Prototype test data are given in parenthesis. Model inputs are marked with an asterisk (*).

The on orbit performance of a flight cryostat has been estimated using the same model, but with a replacement of the manually actuated cryovalves in the internal cryostat manifold and their radiation leaks with COTS, flight qualified, stepper motor driven cryovalves and their smaller conductive heat leak. These valves were first used on SHOOT and have subsequently been successfully used in many other space qualified cryostats. This increases the heat load to the neon to more than double the heat load in the ground simulation, decreasing the neon lifetime to 15 days. This change, however, decreases by an order of magnitude the heat load to the helium. Including the boiloff from the estimated "heater power" necessary to keep the neon solid during the launch hold, and using the efficiency of the conversion from normal to superfluid demonstrated in ground test (57%), we predict that the predicted lifetime, for the proposed flight cryostat, depending on whether the launch is at first (65 hours) or last (161 hours) opportunity, is greater than 15 or 6.5 days (respectively).

Instrument Results

The instrument structure is principally a scaled version of the one developed for LPE[11], but without the "flex plate". The multipurpose probe design has three stages of thermal isolation with GRT servo control in addition to a sample stage with high resolution thermometer (HRT) servo control. The multipurpose probe design also has one stage of thermal isolation with GRT servo control shared by all SQUID sensors. The multipurpose probe design supports 4 SQUID sensors that can be used for any combination of superconducting readout devices (HRTs, pressure sensors, etc.). The miniHRT used on the sample stage of the instrument utilizes a Lanthanum diluted Gadolinium Trichloride ($Gd_{1-X}La_XCl_3$) salt. The thermometer was "self charging" utilizing a permanent magnet for the magnetic field used to bias the paramagnetic salt[12].

The cylindrical volume within the radiation shield for the experiment specific sensor package is approximately 10.9 cm in diameter by 11.1 cm deep, exceeding the development requirement by a factor of two. The multipurpose probe prototype also included a circulator line for precooling the instrument, as well as lines for sample fill and pneumatic (prelaunch) actuation of a normally closed cryovalve. For testing, the probe prototype contained a 50 cc liquid ^{4}He sample cell.

A voltage to temperature calibration of the miniHRT subsystem was achieved against a calibrated GRT. The sensitivity of the miniHRT with dc SQUID readout at 2.17 K was ~ 29 $\emptyset_0/\mu$K.

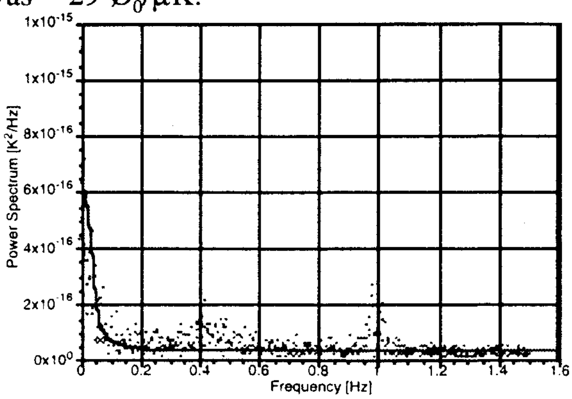

Figure 4 Sample Noise Power Spectrum During mHRT Control

The sample noise power spectrum during HRT control is shown in Figure 4. The noise spectrum was fitted to the following formula which can be derived from the fluctuation dissipation theorem plus a constant for the background from the SQUID noise.

$$\left(T^2\right)_{f+} = \frac{4\tau k_B T^2/C}{\left(1+4\pi^2\tau^2 f^2\right)} + \text{constant} \qquad (1)$$

The integrated noise from this fit from 0 to 1 Hz is just under 5 nK (4.975 nK) at 2.17 K. This exceeds the development requirement for the prototype. The peaks at 0.4 and 1 Hz correspond to temperature fluctuations on the other stages of the instrument which were not optimally controlled. We note that 1 Hz is the frequency of square wave used in the bridge of the LTC-21 controller that was used to control one of the upper stages of the instrument.

Instrument Electronics Results

The issues driving the instrument electronics design came from the desire to support several investigators over the course of multiple reflights of the facility payload. In order to do this, the system needed to be modular and provide a method by which individual investigators could develop a high fidelity testbed for development of their own investigation specific circuits should they desire.

For these and other reasons, a Versa Modular European (VME) bus architecture was chosen. Another benefit of using the VME standard bus is the availability of COTS processors, including radiation hardened versions for flight use.

Another major development in the approach taken is the use of a Digital Signal Processor (DSP) interface between the VME bus and the sensor interface circuits[13]. This approach solved some of the real time interrupt response problems seen in the single processor system used on LPE and CHeX. In addition, this approach provides scalable processing power, including programmable signal processing and control at the board level.

The target processor chosen was the DY 4 SVME/DMV-177 with Motorola PowerPC™ 603e RISC CPU running a VxWorks Real Time Operating System (RTOS). The interface to the host workstation was via ethernet. The user interface on the host workstation was implemented in Labview.

Each of the two GRT cards contained: GRT readout electronics, heater drivers, temperature control servos, and the embedded DSP processor; all sufficient to each control two individual GRT based temperature controlled stages (i.e., four channels of control authority reside on two cards). The DSP chosen was the Analog Devices 2181. The interface between the VME bus and the DSP was achieved via a Xilinx 4013E Field Programmable Gate Array (FPGA). The design utilizes AC current excitation and synchronous demodulation techniques to obtain high noise immunity. The GRT reference digital to analog converter is 16 bit. The temperature servo is a digital Proportional/Integral type servo implanted completely in software that resides in the local embedded DSP. Each card contains circuitry for individual calibration of both channels of thermometer and heater signals. The cards themselves contained surface mounted components on multilayer printed wiring boards

Noise measurements for all GRT channels were made using a 10K resistor to simulate the GRT resistance. As reported in the table below, the noise density is around 33 µK/√Hz RMS which is a combination of the current source noise, the GRT and reference resistance Johnson noise, the preamplifier noise, and some contribution from the digital feedthrough at the multiplying DAC.

The FACET temperature measurement resolution specification was 40 µK RMS for a 1 Hz measurement bandwidth, for 10000 ohms/K, and for a 1.0 µA RMS excitation current. The excitation current for these measurements was 0.707 µA RMS, and the numbers listed in the table accounts for the difference between the two excitation currents.

Table 1
Instrument Electronics Performance

Parameter	Requirement	Measured Performance
GRT Sensitivity @ 10 KΩ GRT Resistance	< 40 µK/√Hz	3.3 µK/√Hz
GRT Time Constant	< 60 Seconds	2 seconds
GRT Drift	< 30 µK/Hour	30 µK/19 Hours
Heater Power Command Accuracy	< 0.02%	0.0028%

Program Benefits

Already the FACET development has produced synergistic benefits to the Low Temperature Microgravity Physics Facility (LTMPF) planned for the ISS through the production of a prototype of a portion of the instrument control electronics also necessary for that facility.

Flight development of the FACET approach would produce an augment to LTMPF. It would provide a "Quick Look" Capability for technology (e.g. dc SQUIDs) and the environment (e.g. Charged Particle Heating in the ISS orbit). It could also enhance the science return from LTMPF by permitting early tests of parameter/technique choice, or measurements of other parameters necessary for data analysis, but that would be too expensive to do simultaneously. In the short term it could serve as a "bridge facility" to address the existing "manifest gap", and after the availability of the ISS, then be available for future science that does not require full capabilities of LTMPF.

The FACET development also has potential cross cutting applications beyond the microgravity program. The architecture is well suited to conducting compact microcalorimeter measurements, such as measurements of the diffuse x-ray background. The cryostat design in particular is well suited to NASA's emerging developments in long duration balloon based experiments.

Summary

The agreement between data and numerical simulations from the model used to design the cryostat indicate that the lifetime of the prototype cryostat is limited principally by radiation "leaks" around the manual operators for the cryostat manifold cryovalves. Modeling indicates that a flight cryostat with COTS, flight qualified, stepper motor driven cryovalves would be capable of cooling an instrument for nearly the full duration of even the longest shuttle missions (16 days). The ground tests have proven the ground hold feasibility of the "no pump" hybrid solid neon - liquid helium design for use on the Hitchhiker Siderail (HH-S) carrier.

The sample temperature control in these preliminary measurements was clearly limited by the thermal control in the "upper" stages during this first cool down and operation of the "generic" instrument. Some changes to the heat sinking of the leads in the instrument are under consideration to lessen these effects. The cryovalve performed reliably. High thermal stability instruments for measurements of the thermodynamic properties of liquid helium are clearly feasible within the FACET cryostat.

The operation, in parallel, of all four parallel channels of GRT readout, heater drive, and temperature control servos, has demonstrated the feasibility of the instrument electronics approach to monitor and control the temperature of a multiple GRT based thermal control stage instrument within a FACET payload.

With each subsystem prototype completed within one year from concept to testing, and within tight cost constraints, the FACET prototype development has proven the feasibility of a simple, low cost, facility providing frequent flight opportunities for a cryogenic Hitchhiker siderail carrier payload on the Space Shuttle.

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References

[1] Nash A, Shields P, Jirmanus M, and Zhao Z. The Development of the FACET Cryostat, to appear in Advances in Cryogenic Engineering.

[2] Petrac D, Israelsson U, and Luchik T. The Lambda Point Experiment: Helium Cryostat, Cryoservicing, Functions and Performance. Advances in Cryogenic Engineering, 38, 1993.

[3]JPL D-11781. Low Temperature Platform Briefing Document. 1994.

[4] NSTS 1700.7B, Safety Policy and Requirements for Payloads Using the Space Transportation System. 1997.

[5] P.J. Shirron, J.L. Zahniser, and M.J. DiPirro, A Liquid/Gas Phase Separator for He-I and He-II, Advances in Cryogenic Engineering, 37, (1992).

[6] P.J. Shirron, M.J. DiPirro and J. Tuttle, Flight Performance of the SHOOT Liquid Acquisition Devices, Cryogenics, 34, (1994).

[7] Lysek M. J., Israelsson U. E., Chui T. C. P., and Larson M. E. Design and Testing of an Improved Cryopump for the Confined Helium Experiment. Advances in Cryogenic Engineering, 43: 995-1000 1998.
[8] McCammon D, Almy R, Deiker S, Morgenthaler J, Kelley RL, Marshall FJ, Moseley SH, Stahle CK, Szymkowiak AE. A sounding rocket payload for X-ray astronomy employing high-resolution microcalorimeters. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 370: (1) 266-268 FEB 11 1996.
[9] Mills G. Design and Development of a Leak Tight Helium II Valve with Low Thermal Impact. Advances in Cryogenic Engineering, 37: 1425 - 1432 1992.
[10] Lockhart JM, Muhlfelder B, Gutt GM, et al. Optimization of a SQUID system for space. IEEE T APPL SUPERCON 7: (2) 2534-2537 Part 3 JUN 1997.
[11] Lipa J. A., Chui T. C. P., Nissen J. A., and Swanson D. R. A low temperature system for advanced thermal control. Temperature its measurement and control in Science and Industry Vol. 6; No. 2 : 949-952 1992.
[12]Welander P., Barmatz M., Hahn I. A new small nano-Kelvin resolution thermometer for low temperature experiments. Proceedings of the 16th IEEE Instrument and Measurement Technology Conference, vol.1, 413 (1999).

[13] Williamson P.R., Bumala R.W., Lipa J.A. Station Processor and Electronics Control (SPEC): New Techniques for Realtime Data Acquisition and Control of Experiments on the External Facility of the Japanese Experiment Module. Proceedings of the 21st International Symposium on Space Technology and Science. Sonic City, Omiya, Japan, 1998.